

WORLDWIDE STATUS OF WIND-DIESEL APPLICATIONS

E. Ian Baring-Gould
Senior Engineer
National Renewable Energy
Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393
USA
303 384-7021/7097
ian_baring_gould@nrel.gov

Larry Flowers
Team Leader
National Renewable
Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393
USA
303 384-6910/7097
larry_flowers@nrel.gov

Per Lundsager
Senior Scientist
Riso National Laboratories of
Denmark
PO Box 49
DK-4000 Roskilde
Denmark
(+45) 4677 5045
per.lundsager@risoe.dk

Lawrence Mott
Senior Engineer
Northern Power Systems
P.O. Box 999
Waitsfield, VT 05673-0999
USA
802 496-2955/2953
lmott@northernpower.com

Mari Shirazi
National Renewable
Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393
USA
303 384-6991/6901
Mari_Shirazi@nrel.gov

Juergen Zimmermann
Powercorp Pty. Ltd.
3406 Export Drive
Trade Development Zone
Darwin NT
Australia
+61 889 225124
juergen@pcorp.com.au

ABSTRACT

Over the past few years, the market for wind-diesel power systems has evolved from a topic of discussion for researchers to the installation of a number of commercial operating systems. From Alaska to Chile, from Australia to Spain, from high-penetration wind-diesel plants to wind-diesel-hydro systems, the integration of wind turbines and conventional isolated grid generation is a commercial reality. While small, DC-based, renewable hybrid power systems are commercial, the technology for large-scale AC hybrid systems is now emerging as a commercial reality. A key recommendation from participants at a recent wind-diesel workshop sponsored by the U.S. Department of Energy (DOE), American Wind Energy Association (AWEA), and Canadian Wind Energy Association (CanWEA) was to document and communicate the current state of the technology, the economics, the applications, the operating experience, and the commercial prospects for this international solution. This paper presents the first steps in conducting this level of reporting.

INTRODUCTION

At the 2002 DOE/AWEA/CanWEA wind-diesel conference in Anchorage, Alaska, a seed shift was noted in the wind-diesel power systems market. At the previous conference in September 2000, discussions focused on installed systems and work that could be done. As with previous meetings, this one was driven by researchers discussing the technology and "how we could do it." The Anchorage meeting proved that the tides are turning: Discussion focused on how systems have been working and what barriers have been faced in the installation and operation of remote power systems.

This is a very exciting time for this industry. Research into systems continues as researchers receive feedback from operators and plant managers about how the systems are working. This paper describes the current state of the art of wind/diesel technology and applications, the current research activities, and the remaining technical and commercial challenges. System architectures, dispatch strategies, and operating experience from a variety of wind/diesel systems from around the world will be reviewed.

Because of the large number of isolated diesel minigrids in both the developed and developing world, the market for retrofitting these systems is substantial. Because this market represents an international opportunity, a community of interest has formed and is committed to sharing the technical and operating experience to expand the recent commercial successes.

THE WORLD OF OFF-GRID ELECTRIFICATION

Wind/diesel power systems can be more accurately described by the title “hybrid power system.” Such a power system can incorporate different components, including production, storage, power conditioning, and system control to supply power to a remote community.

The classic hybrid system incorporates renewable technology, a fossil fuel engine generator(s), a battery bank, and a power converter. In most cases, this system is based on a two-bus system: a DC bus for the battery bank and an AC bus for the engine generator and distribution. The renewable technology may be attached to either the AC or DC bus depending on the system size and configuration. These systems usually supply AC power, although some loads may be tapped off the DC-bus bar. This power system configuration is used for larger communities and can range in size from 4 kilowatt-hours (kWh)/day to many megawatt-hours (MWh)/day, with no firm boundary on either side.

This general configuration can have a great deal of internal variability, depending on the system size. Smaller systems will likely use large battery banks, providing up to a few days of storage to cover the average load, and will use smaller renewable generation devices connected to the DC bus. These systems focus around the DC-bus bar, with the production of AC power coming from a power converter or diesel engines. Larger systems focus on the AC-bus bar, with all renewable technology designed to be connected to the AC distribution network. In larger systems, the battery bank (if used at all) is generally small and mainly used to cover fluctuations in power production. Larger systems usually contain more and larger equipment that allows for an economy of scale, and thus lower power costs.

In systems that focus around the DC bus, the battery bank acts as a large power dampener, smoothing out any short- or long-term fluctuations in the power flow. In many ways, it regulates itself based on a few specific parameters. This is not the case with equipment connected to the AC grid, which is much less forgiving. The key issues are the balancing of power production and load and voltage regulation on a sub-cycle time scale. This is largely done with the use of synchronous condensers, dispatchable load banks, short-term storage, power electronics, and advanced control systems that carefully monitor the operating conditions of each component to insure that the result is power with a consistent frequency and voltage.

TOPOGRAPHY OF LARGE HYBRID POWER SYSTEMS

The first critical step when implementing larger AC bus systems is to determine which renewable-based generation technology will be applicable for the site in question. Three types of technologies are commonly found: wind/diesel, photovoltaic (PV)/diesel, and hydro/diesel. Many other combinations can and have been considered. In the case of both PV and hydro/diesel plants, the short-term fluctuations in the renewable production that are generally experienced in wind/diesel systems are not present. Hydro/diesel systems are either very large (multi-megawatt) or seasonal in nature; thus, they don't experience large power fluctuations. PV/diesel systems usually incorporate large battery banks to provide storage of solar energy for evening loads and thus do not experience fluctuations that affect power conditions on the AC bus. However, some recently considered PV/diesel systems with AC PV panels or production-on-demand solar would experience some of the same power fluctuation issues as wind-based systems.

Wind/diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid with a minimum of additional features, to more complex systems [1, 2]. Two overlapping concepts depict the system design and required components: the amount of energy that is

expected from the renewable sources (system penetration) and the decision to use a storage device to cover system energy fluctuations. Given today's technology, these issues are usually selected by the system designers as a starting point for system design. Both of these concepts are described in the following section.

RENEWABLE PENETRATION

When incorporating renewable-based technologies into large power systems, the amount of energy that will be obtained from the renewable sources must be determined because this will dictate which components will be used. Steve Drouilhet developed the following classification and definitions of system penetration that characterize the levels of system complexity:

$$\text{Instantaneous Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Primary Electrical Load (kW)}}$$

And

$$\text{Average Penetration} = \frac{\text{Wind Turbine Energy Output (kWh)}}{\text{Primary Electrical Load (kWh)}}$$

The difference in these equations is in the units. Instantaneous penetration is in terms of power; thus, it is the ratio of how much power is being produced by the renewable resources at any specific instant. The average penetration is in terms of energy; it includes a time domain and is thus measured over days, months, or even years. In some sense, average penetration is in the domain of the economist and instantaneous penetration falls in the realm of the engineer. Drouilhet also proposed a three-level classification system based on system penetration that separates systems along power and system control needs (Table 1).

LOW-PENETRATION SYSTEMS: Many low-penetration systems have been installed worldwide. These vary from small to relatively large isolated grids, such as those found on several Greek islands. In fact, some large grids, such as those found in certain areas of the United States and Europe, reach a wind power penetration that would classify them in the same category as low-penetration systems. Basically, low-penetration systems are those in which the renewable generation source is just another source, requiring no special arrangements. The control technology required at this level of generation is trivial, especially given the control, flexibility, and speed of modern diesel and wind systems. In many systems, no form of automated control is required—the wind turbines act under their commercial controllers and an operator monitors all system functions. Because the diesel engines are designed to allow for rapid fluctuations in power requirements from the load, the addition of wind has very limited impact, if any, on the ability of the diesel control to provide the remaining difference. Issues of spinning reserve, a term used to represent the availability of instantaneous system capacity to cover rapid changes in system load or energy production, are addressed by the allowable capacity of the diesel engines, which in many cases can run at 125% rated power for short periods of time with no adverse impact on the diesel or generator.

MEDIUM-PENETRATION SYSTEMS: Systems with larger ratios of renewable energy contribution fall into this category. Allowing power penetrations of up to 50% will allow any under-loaded diesel generators in multiple diesel plants to be shut off or for production to be switched to a smaller unit. This in turn will reduce plant diesel consumption and reduce diesel engine operation. However, this may also open the power system to potential shortfalls, assuming the loss of one or more of the wind generators or diesel engines. In addition, with a large penetration of energy being produced by the variable renewable source, it will become harder for the operating diesel units to tightly regulate system voltage and maintain

an adequate power balance. There are options to ensure that the high-power-quality requirements of the power system are maintained, even with half of the energy provided by renewable sources. Some of the options include power reduction capabilities within the wind turbine controller, the inclusion of a secondary loads to ensure that no more than a specified amount of energy will be generated by the wind, installation of capacitor banks to correct power factor, or even the use of advanced power electronics to allow real time power specification.

Spinning reserve on medium-penetration power systems requires experience in regard to proper power levels and system commitments but is not considered technically complex. Such spinning reserve questions should be handled on a case-by-case basis but can be partially solved by using options including the use of advanced diesel controls, the installation of a modern diesel engine with fast start and low loading capabilities, controlled load shedding or reduction, power forecasting, and proper system oversight. Combined with the use of variable-speed or advanced power conditional available on many modern wind turbines, the control requirements of medium-penetration systems are quite simple. The ability to provide high power quality in medium-penetration power systems has been demonstrated for years in a number of highly important locations. The most notable examples are the military diesel plants on San Clemente Island and Ascension Island and the power system in Kotzebue, Alaska. All of these systems have experienced power penetration at or above these guidelines set for medium penetration systems.

TABLE 1: PENETRATION CLASS OF WIND-DIESEL SYSTEMS (PROPOSED BY STEVE DROUILHET)

PENETRATION CLASS	OPERATING CHARACTERISTICS	PENETRATION	
		PEAK INSTANTANEOUS	ANNUAL AVERAGE
LOW	<ul style="list-style-type: none"> ▪ Diesel runs full-time ▪ Wind power reduces net load on diesel ▪ All wind energy goes to primary load ▪ No supervisory control system 	< 50%	< 20%
MEDIUM	<ul style="list-style-type: none"> ▪ Diesel runs full-time ▪ At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading or wind generation is curtailed ▪ Requires relatively simple control system 	50% – 100%	20% – 50%
HIGH	<ul style="list-style-type: none"> ▪ Diesels may be shut down during high wind availability ▪ Auxiliary components required to regulate voltage and frequency ▪ Requires sophisticated control system 	100% - 400%	50% – 150%

HIGH-PENETRATION SYSTEMS: Although this technology has been demonstrated on a commercial basis, high-penetration wind-diesel power stations require a much higher level of system integration, technology complexity, and advanced control. The principle of operation of high-penetration systems is

that the required equipment is installed in addition to the wind turbine so that the diesel can be shut off completely when there is an abundance of renewable-power production. Any instantaneous power production over the required electrical load, an instantaneous penetration over 100%, is supplied to a variety of controllable secondary loads. In these systems, synchronous condensers, load banks, dispatchable loads (and possibly storage in the form of batteries or flywheel systems), power converters, and advanced system controls are used to ensure power quality and system integrity. Spinning reserve is created through the use of short-term storage or the maintenance of a consistent oversupply of renewable energy. Although these systems are being demonstrated commercially, they are not yet considered a mature technology and have not been demonstrated on systems larger than approximately 200 kW average load.

STORAGE OR NO STORAGE?

Until recently, it was assumed that wind-diesel systems without storage were theoretical, possibly born out of short-term testing in test-stand-based power systems. This is no longer the case. Commercially operating short-term and no storage systems have been installed in recent years, demonstrating that either technology choice is viable.

In systems incorporating storage, the storage is used to cover short-term fluctuations in renewable power. The premise of this system design is that a large penetration of renewables is used (up to 300% of the average power requirements), and when the renewable-based generators are supplying more power than is needed by the load, the engine generators can be shut down. During lulls in the renewable power generation, discharging the battery bank or other storage device supplies any needed power. If the lulls are prolonged or the storage becomes discharged, an engine generator is started and takes over supplying the load. Studies have indicated that most lulls in power from the wind are of limited duration, and using storage to cover these short time periods can lead to significant reductions in the consumption of fuel, generator operational hours, and reduced generator starts [3,4].

In large power systems, the installation of a battery bank to cover shortfalls in renewable production may not be feasible, mainly due to cost. However, without the use of storage, it is very difficult to control the stability of a conventional power grid with large quantities of renewable power—thus the challenge of hybrid systems without storage. This configuration is based on the AC bus and does not use batteries to provide grid stabilization. The basic premise of these systems is that the installed capacity of the renewable technology is much larger than the load. When the renewable devices are operating and producing more energy than is needed by the load by some margin, usually between 125% and 150%, the dispatchable generators can be turned off. External control devices, such as dispatchable secondary loads, fast acting dump loads, synchronous condensers, and advanced diesel control are used to maintain system stability and control. If the renewable energy dips below a specified threshold, a generator is started to insure power security or some of the dispensable loads can be disconnected to increase the systems headroom. This type of system produces a large amount of extra energy that must be used if the project is to be economical.

All high-penetration systems, with and without storage, have been installed in northern climates where the extra energy can be used for heating buildings or water, displacing other fuels. In these systems, it may be wise to install uninterruptible power supplies (UPSs) on critical loads. Although few systems have been installed, the concept is economically attractive and can drastically reduce fuel consumption in remote communities.

MARKET SUMMARY

One of the major market drivers for the hybridization of diesel power systems with renewable technology is the relatively high cost of producing power with diesel engines. Cost for delivered fuel to remote sites can be high (\$3.50/liter for the extreme case of the South Pole), as is the cost of storage of diesel fuel in

areas that may only receive one fuel shipment per year. Even in more accessible areas, the lowest bus bar cost of energy from diesel production is around \$0.15/kWh, but it can be much higher than this in small or remote communities. This raises the bar to allow other renewable-based technologies that may not be commercial in strictly economic terms when connected to a national grid.

The true market for the retrofitting of diesel power plants using renewable energies has always been elusive. This is also seeing a seed change in the industry. It became clear through discussions and presentations at the wind-diesel conference that the proposed market is not as elusive as it once was. Reports from all over the world described the current market conditions for this technology. The following subset of reports relates to wind systems:

ALASKA

Alaska represents one of the near-term markets for the implementation of wind-diesel systems. The three operational systems at Kotzebue, St. Paul, and Wales provide strong field demonstrations of the technology that is helping to sway public opinion. The high cost of fuel and fuel storage and a strong push for locally supplied power sources are also spurring the market for wind-diesel applications. Alaska also has more than 90 rural communities that are in areas with Class 5 to 7 winds, based on a wind resource map produced by the National Renewable Energy Laboratory (NREL). An additional factor is that due to the level of service provided, loads tend to be large. Alaska's climate also supports the concept of higher-penetration systems because any waste energy can be used for space heating. Funding for projects is also available through a number of federal and state government channels, as well as native and other private corporations [5].

CANADA

The second-largest market for diesel retrofit technologies is likely in remote Canada, which currently has more than 300 remote communities currently being supplied by diesel generators. Programs for retrofitting these systems will examine all renewable-based technologies, including biomass, micro-hydro, and solar, in addition to wind energy. Canada does not have a detailed wind map, as is available for Alaska, but many of the remote communities are located along the northern and Pacific coasts, areas of demonstrated wind resource. Although the Canadians are not moving to implement the technology in the near term, as more experience is gained by systems operating in Alaska, this could be a secondary market of significance.

AUSTRALIA

Australia is another example of a country with a many remote communities that are supplied through diesel power stations. However, most of the rural communities are located in the center of the country where the available wind resources are limited. More potential for wind-based systems exists in the coastal regions of Northern Australia and on some islands, although technical issues regarding turbine safety in cyclonic-prone areas must be addressed. Territorial Australia also includes a number of remote islands, which could also be reasonable sites for a wind retrofit of existing diesel stations. Australia also has favorable policies in place to reduce the country's dependence on diesel power generation. The Australian Greenhouse Office provides a subsidy of up to 50% of the cost of the renewable components for systems that will reduce fuel consumption, either based on new or retrofit generation facilities. The infrastructure within Australia is also well advanced, both in regard to existing power systems and technological understanding. There are four wind-diesel power systems currently in operation around the country, ranging in size from 1.2- to 14-MW peak load, representing low- and middle-penetration levels. There are also many more PV-diesel systems that use similar technology and control systems. Australia also boasts several leading research and commercial institutions in the field of renewable technology and diesel retrofit research [6].

CHILE

The only other country that is actively implementing wind-diesel power systems is Chile. Due to the geography of the southern regions of the country, which are very similar to the panhandle of Alaska, many remote communities are served by diesel power systems. The mountains and coastal regime of southern Chile also provide localized opportunities for wind and hydro/diesel systems. Unlike most near-developed countries, Chile has an active industry and programs in diesel retrofit technology. This includes the privately financed installation of a 2.0-MW wind plant into a 14-MW peak diesel/hydro power system in the community of Coyhaique and the pursuance by the Comision Nacional de Energia in the analysis of retrofitting options for the diesel plant on Isla de Robinson Crusoe and several other power stations. The exact numbers of remote diesel plants have not been assessed, and more detailed wind resource assessments must be completed before the market's true value will be known [7].

ADDITIONAL SUPPORTING MARKETS

A number of other countries are investigating or have considered diesel retrofit technologies using wind energy. However, these markets are constrained in some fashion, making it difficult to assess their potential. Examples include the Philippines, which has identified approximately 20 remote diesel systems that could be retrofitted with wind technology. In many cases, sites have been identified and site-specific wind monitoring conducted; however, financial and regulatory barriers hinder project implementation. Argentina is in a similar situation, with 11 remote diesel stations in the province of Santa Cruz alone producing more than 40,000 MWh per year in an area with wind speeds above Class 4. Although the local utility, Servicios Publicos de Santa Cruz, is in the process of installing one 50-kW wind turbine on the large diesel station in the community of El Calafata, the current economic condition of the country limits the near-term market for wind-diesel technology. Brazil, like Australia, has a large subsidy program that can be used for renewable technologies that reduce diesel fuel consumption. However, the market is weak, and there is limited potential for wind retrofit of remote diesel stations due to the generally low wind speeds in the northern provinces of Amazonas and Para. The final market for diesel retrofit or new power system development is China. Once again, great distances and high transmission line costs and losses have resulted in a large number of remote diesel plants. The Chinese central government is currently undergoing a major program to install renewable-based power systems in all regional townships, to be followed by an even loftier program to supply the approximately 22,000 rural villages with electrical service, primarily using renewable technology. These systems are generally small by wind-diesel standards and, due to the poor availability of wind resource data, are primarily being implemented as PV or PV-diesel systems. However, a large number of islands in coastal China could benefit from the retrofit of the existing power stations with wind technology. This market, however, has not been classified or rigorously documented. Development issues also persist in mainland China, and larger systems are not being implemented without development assistance [8].

Other large markets have been discussed but are not reflected in this survey. They include Indonesia, which faces stability and financing problems; Russia, which has a very large potential market but limited capital for retrofit technology; Mongolia, which has a great wind resource but limited access to development funds; Colombia, which supports hundreds of remote diesel stations but has limited wind resource and is politically unstable; and India, which also lacks funding sources and information on developable large-scale wind-diesel systems. Other opportunities, such as Africa, exist; however, significant work and time would be required to further define them.

RESEARCH ACTIVITIES

Research into wind-diesel systems has also been conducted to strengthen the technology. The area of controls for power systems, primarily focused on higher-penetration power systems, is one of the strong research areas. Other research issues include stand-alone inverter testing and development of stand-alone wind turbines. The key organizations represented at the workshop included the Australian Cooperative

Research Center for Renewable Energy (ACRE); the U.S. Department of Agriculture (USDA) research station at Bushland, Texas; Riso Laboratories of Denmark; the Alternative Energy Institute of West Texas A&M University; the Hydro-Quebec Research Institute (IREQ); the Canadian Atlantic Wind Test Site (AWTS); and NREL.

Some of the more interesting research includes work at Riso into the development of a stand-alone wind turbine that would be capable of cold startup from a de-energized grid and power production without additional grid support. Currently this work is being conducted on an 11-kW wind turbine, which has already been tested in grid-connected and diesel power grids [9]. Another interesting project has been the completion of a hybrid system industry assessment by the Alternative Energy Institute of West Texas A&M University. This report describes the state of the hybrids industry and provides good case studies of the power systems installed in Kotzebue, Alaska, and Xcalac, Mexico [10]. The report addressed hybrid power systems above 4kW in size and includes an extensive list of operating hybrid power systems. Both NREL and ACRE are conducting tests on power converters. NREL is testing new advances in large power converters, looking at reactive power production to allow stand-alone operation with induction wind turbines. ACRE is developing test procedures for stand-alone power converters. The USDA Bushland test site has also been comparing the operational performance of different systems configurations with and without storage. Some results of the analysis, which show the impact of the use of storage on diesel, wind-diesel, and wind-only system operation are shown in Table 2.

TABLE 2: RESULTS OF THE USDA BUSHLAND TEST SITE ANALYSIS OF THE IMPACT OF STORAGE ON THE PERFORMANCE OF DIFFERENT POWER SYSTEM CONFIGURATIONS

	Diesel Only	Battery Diesel	Wind- Diesel Without Storage	Wind- Diesel With Storage	Wind Without Storage	Wind With Storage
Total Production (kW)	15652	2745	31278	2401	1485	2941
Total Load (kW)	15470	2551	15043	1913	348	893
System Efficiency	99%	93%	48%	80%	23%	30%
Specific Fuel Consumption l/kWh	0.38	0.38	0.25	0.10	N/A	N/A

The other primary area of research focuses on the development of controls for high-penetration power systems. IREQ continues to work in the field of high-penetration, no-storage-system controls, and it assisted Northern Power Systems in the development of the control structure for the St. Paul power system in Alaska. Both the AWTS and USDA are conducting research on integrated control packages for wind-diesel power systems. The USDA project has been completed in conjunction with Northern Power Systems and Encorp Co. and has received testing at the USDA hybrid system test stand in Bushland. The AWTS – Wind-Diesel Integrated Control System has undergone development and testing at the test site on Prince Edward Island and has been integrated into the demonstrative system on Sagar Island in eastern India. NREL has conducted development activities around dispatch strategies for high-penetration systems that could be incorporated into commercial programmable logic controllers. This work was conducted using NREL’s Hybrid/Distributed Energy Test Facility and was implemented in the Wales, Alaska, high-penetration system. Riso has developed a modular supervisory control concept [11], in which the running control and regulation tasks are handled by the component controllers, while the supervisory-decision-type tasks (unit commitment) are handled by a supervisory controller with a flexible, modular layout. The concept has been validated on Riso’s experimental WD system [1].

MODELING AND SIMULATION

Another area that was discussed at the conference was the continued development of simulation models for hybrid wind-diesel power systems. Presentations on three models were given: the HOMER software developed at NREL, the Hybrid2 model developed by the University of Massachusetts, and a new model developed at IREQ that uses Simulink and the MatLAB Power System Blockset to analyze the dynamic response of wind-diesel applications. Although not discussed, NREL has also developed an additional dynamic systems software based on the VisSimTM analysis software. RPM-SIM allows the analysis of the dynamic performance of wind/PV/diesel power systems with and without storage [12].

The HOMER software is a broad-based optimization tool that is used to determine a basic system design given a specified resource, community load, and certain economic parameters. The model considers wind, PV, battery, micro-hydro, small modular bio-power, hydrogen, and diesel technology in its analysis. It is a very good screening model that allows a system designer to determine the basic system configuration before detailed design and analysis begin. It includes a sensitivity analysis capability that automatically reruns the model over a user-specified range of key input parameters. The most recent version of the software, version 2.0, allows the use of multiple diesel generators and can analyze systems with or without storage. The code only uses one-hour time steps and thus is more applicable to long-term performance modeling or component sizing. It would have to be followed by more detailed analysis of system performance issues for high-penetration wind/diesel systems [13].

The Hybrid2 software was designed as an engineering analysis tool to consider the performance of remote power systems with special consideration to high-penetration systems with or without storage. The code can model many combinations of wind turbines, photovoltaic arrays, diesel generators, power converters, and battery storage in AC, DC, or two-bus systems. Hybrid2 also allows for more than 100 dispatch configurations with multiple diesel generators, renewable sources, and battery storage. Recent development in the software allows modeling of diesel generators that do not have a linear fuel vs. performance curves (a typical assumption for most performance models) and also allows the analysis of process or excess heat usage [14,15].

The MathWorks Power System Blockset for use in the Simulink environment was created by IREQ and allows the modeling of power systems, including remote power applications. The tool allows the dynamic analysis of multiple source technologies, including all the choices applicable to wind/diesel power systems. The open modular environment of the Simulink software allows flexibility in system design and the ability to simulate the mutually interactive components of a dynamical system. The software can be used for system design optimization and analysis of dynamic system behavior due to changes in the system input state [15].

Riso's WINSYS model [16] is used to assess the levelized performance of wind/diesel systems in up to 20-year-lifetime scenarios. This model is different in that it allows for economic factors, such as electrical rates and component prices, and technical configuration information, such as the number and specification of the different wind turbines, to change over the life of the system. This concept is presently being extended into the IPSYS model for integrated power systems.

DEMONSTRATED HYBRID POWER SYSTEMS

The strongest indication of the growth in wind-diesel technology was the number of power systems that were discussed. During the conference, 12 presentations were given, providing experience in the operation of more than 17 wind-diesel power systems from around the world. In this paper, the authors have selected five wind-diesel implementation projects that show the varied options for using diesel retrofit technology. These systems are applicable in areas other than those with highly developed infrastructure and access to technical support.

THE WALES, ALASKA, WIND-DIESEL HIGH-PENETRATION HYBRID POWER SYSTEM

To reduce the cost of rural power generation and the environmental impact of diesel fuel usage in remote Alaskan communities, the Alaska Energy Authority (AEA), Kotzebue Electric Association (KEA), and NREL began a collaboration in late 1995 to implement a high-penetration wind-diesel hybrid power system in a village in northwest Alaska. The project was intended to be both a technology demonstration and a pilot for commercial replication of the system in other Alaskan villages.

Following local resource assessments and other studies, the native Inupiat village of Wales was selected as the final demonstration location. This community of approximately 160 inhabitants sits on the western tip of the Seward Peninsula, looking out onto the Bering Strait. The average electric load for the community is about 70kW, although there are also substantial heating loads for buildings and hot water.

The Wales wind-diesel hybrid power system, which underwent final commissioning in March 2002, combines three diesel generator sets with a combined power of 411 kW; two 65-kW AOC 15/50 wind turbines; and a 130-Ah battery bank made up of SAFT nickel cadmium batteries, an NREL-built rotary power converter, and various control components. The primary purpose of the system is to meet the village electric demand with high-quality power, while minimizing diesel fuel consumption and diesel engine run time. The system also directs excess wind power to several thermal loads in the village, thereby saving heating fuel [17].

Limited data have been taken on system operation in all the different modes of operation, but one 18-day test period during August 2002 reported wind-only power system operation for 20% of the system operating time. August represents one of the lower wind speed month in Wales. During this same test period the wind turbines supplied 41% of the consumer load, while the diesel engine supplied the remaining 59%. The wind turbines also supplied almost 10,000 kWh of electric energy to the system heating loads, saving an estimated 450 liters of heating fuel. It is expected that the two wind turbines will provide an average penetration of approximately 70%, saving 45% of expected fuel consumption and reducing the operational time of the diesel engines by 25%.

The retrofit of the diesel plant and implementation of the high-penetration system has not been without problems. A number of these implementation issues have been reported in a paper by Drouilhet [18].

THE ST. PAUL, ALASKA, HIGH-PENETRATION WIND-DIESEL POWER SYSTEM

The Tanadgusix Corporation (TDX), a native Alaskan corporation, needed a stand-alone power system for its facility on the island of St. Paul in the Bering Sea. The site is an airport/industrial complex with airline offices, equipment repair, and storage facilities. TDX wanted to reduce the overall energy costs for the camp's electrical and heating loads, while maintaining reliable, utility-grade electrical service. In 1999, Northern Power Systems installed a high-penetration, no-storage hybrid power system that maximizes the contribution of St. Paul's abundant wind resource. The primary components of the Saint Paul plant include a 225-kW Vestas V27 wind turbine, two 150-kW Volvo diesel engine generators, a synchronous condenser, a 27,00 liters (6,000 gallon) insulated hot water tank, approximately 305m (1,000 feet) of hot water piping, and a microprocessor-based control system capable of providing fully automatic plant operation.

The primary electrical load for the facility averages about 85 kW, but the system also supplies the primary space heating for the facility, which it does with excess power from the generators and thermal energy from the diesel plant. When the wind generation exceeds demand by a specific margin, the engines automatically shut off and the wind turbine meets the load demand with excess power diverted to the hot water tank, which in turn is used to heat the complex. When wind power is insufficient to meet the load,

the engines are engaged to provide continuous electric supply as well as provide energy to the hot water system when needed. The total 500-KW wind/diesel cogeneration system cost approximately \$1 million. Its operation has eliminated \$200,000 per year in utility electric charges and \$50,000 per year in diesel heating fuel. Since its installation, the load has continued to grow and additional thermal heating loops have been added to the facilities [19,20].

THE ALTO BAGUALES WIND-HYDRO-DIESEL POWER SYSTEM IN COYHAIQUE, CHILE

The power utility EDELAYSEN S.A., part of the SAESA Group of Chile and a subsidiary of Public Service Enterprise Group of New Jersey, operates a number of remote diesel and hydro stations in the XI Region of southern Chile. The largest of these systems supplies energy to the regional capital of Coyhaique. The system provides a maximum power of 13.75 MW, which until recently was supplied by a large hydro–diesel power station. In the fall of 2001, the company installed three 660-kW Vestas wind turbines to supplement the diesel and hydro production. The Alto Baguales wind energy project is expected to provide more than 16 % of the local electric needs. This is the first wind generation project in Chile, and it will displace current diesel generation and help to improve air quality. It is expected that the project will displace about 600,000 liters (158,500 gallons) of diesel fuel per year, which will reduce CO₂ emission by more than 13 million pounds per year. It will also lower costs for power overproduction with diesel technology in this remote location [21].

The turbines are operated remotely from the diesel plant and operate at around a 50% capacity factor due to strong winds at the turbines site. To date, the highest recorded penetration, based on 15-minute instantaneous readings taken at the power station, is 22% of total demand. In the summer of 2003, EDELAYSEN will finish the installation of additional hydro capacity that will allow the utility to provide the whole load with wind and hydropower, completely eliminating diesel production. Depending on the results of this operation, more wind energy could be installed at the Alto Baguales site. The primary challenge of the project implementation was obtaining the proper installation equipment, including a crane that had to be brought in over the mountains from Buenos Aires, Argentina.

CAPE VERDE POWER SYSTEMS, CAPE VERDE

The Archipelago of the Republic of Cape Verde consists of 10 major islands off the western coast of Africa. Although the experience with modern wind turbines on the islands has been mixed, partly due to a lack of local experience and proper maintenance, three medium-penetration wind-diesel systems have successfully provided power to the three main communities of Cape Verde: Sal, Mindelo, and Praia. These power systems are very simple in nature and contain a minimum of additional system control or power smoothing equipment (basically a dump load and a wind turbine shut down function to keep minimum diesel load conditions). The 3x300-kW NKT wind turbines are connected to the existing diesel distribution grid at each site in standard grid-connected mode. The average loads for the communities vary from 1.15 MW for the smallest, Sal, to 4.5 MW for the largest, Praia (the nation's capital). At the present time, in Phase 1 financed by Danida, the power systems operate at average monthly wind energy penetrations of up to 25%, depending on the system and time of year. Yearly penetrations of between 14% for Sal and Mindelo and 6.3 % for Praia have been experienced. The average wind turbine capacity factor for the first 3 years of operation has been as high as 55%, and the maximum average monthly wind power penetration of 35% was reached in Sal with no adverse system impact. The overall experience of the three wind farms has been perceived by the utility ELEKTRA as quite positive and has resulted in the initiation of Phase 2, financed through the World Bank and managed by Cape Verde, in which penetration of wind energy in these three power systems will be almost doubled.

To assess the impact of adding additional wind energy to these systems in Phase 2, Riso National Laboratories of Denmark has conducted a detailed assessment of the systems using the WINSYS

modeling software [11]. The expansion of these systems is expected to increase the wind energy penetration in the first year of operation to levels ranging from 18% (Praia) to 30% (Mindelo). The wind energy penetration leveled over the entire 20-year operating life is expected to be somewhat lower due to the installation of additional diesel generating power. The average annual diesel fuel consumption is expected to be reduced by more than 22.25 million liters (5.96 million gallons) from the current experienced savings of approximately 16.83 million liters (4.44 million gallons) [22].

DENHAM WIND-DIESEL POWER STATION, WESTERN AUSTRALIA

The Denham wind-diesel power station is operated by Western Power and is located on the western coast of Australia, north of the regional capital of Perth. The power system has a maximum demand of 1,200 kW, which is supplied by 690 kW of wind from three 230-kW Enercon E-30 wind turbines, four diesel engines with a total rating of 1720 kW, and a recently installed low load diesel. The low load diesel is a standard diesel generator that is modified to allow prolonged operation at very low or negative loads. The device installed in Denham has a load range of +250kW and -100kW. The power system was installed by PowerCorp of Australia and is controlled from a highly automated control center located in the powerhouse using control logic also developed by Power Corp. The power system has the capability to operate in a fully automated mode with minimal technical oversight. The system control allows all of the standard diesel to be shut off, resulting in an average penetration of 50%.

The power system has been operating for more than 3 years, supplying utility-quality power and saving an estimated 270,000 liters (71,300 gallons) of fuel per year [23].

In a separate but similar project PowerCorp recently installed two Enercon E30 300kW wind turbines with the Dynamic Grid Interface 200kW into the Mawson diesel power system in Antarctica. This system, which does not contain storage, has achieved an average penetration of approximately 60% since its commissioning in January 2003.

WORKSHOP CONCLUSIONS/CHALLENGES

The conclusions of the workshop were that older, lower-penetration power systems with successful operation were undergoing expansion; more sophisticated power systems have been installed and were operating; new, highly flexible system controllers are being developed; and there is market potential in several areas to keep the industry moving forward in the years to come. However, several important issues and market barriers were raised during the conference that have yet to be addressed.

One of the key issues identified was the continued reservation in the use of diesel retrofit technology on the part of the people and organizations in a position to make use of the technology. The following sums up the feelings of the participants: "Those who need it, don't have the money. Those with the money don't trust the product. Those with the product don't have a market." Diesel retrofit technology remains expensive, and although it may be competitive on a life-cycle cost basis, the low rate of return limits all investment to government or multilateral organizations with very long payback horizons. These organizations, however, are usually the most difficult to convince of the value of a new technology, and without good demonstration projects with proven results, it can be almost impossible. Finally, without the economies of scale for the implementation of wind-diesel systems, system engineering costs required for each installation increase development costs. In addition, workshop participants expressed concerns that some effort should be made in the area of added-value analysis for retrofitting diesel systems, including issues such as the cost and benefit of claiming CO₂ credits; determining the true value of externalities and the efficiencies of deferrable loads; and better analysis of operation, maintenance, and replacement expenses of components including power electronics, controls, and batteries.

A second issue that was repeated during the conference was the lack of midsize wind turbines available on the market and the reluctance of the industry to supply turbines in small numbers to remote projects. In

an industry that is growing at approximately 30% per year and is producing ever-larger turbines, the availability and support of turbines between 250 and 600 kW is quite limited. Without wind turbine producers willing to supply mid-range turbines to the diesel retrofit market, it will become even more difficult to field projects.

The last issue that was noted by research organizations and companies alike is the reduction in governmental support for research in the area of wind-diesel technology, not only in North America, but also in Europe and Australia, the primary regions where technology development has occurred in the past.

Unfortunately, the only forward-looking steps that could be counted on at the conclusion of the conference was the expressed commitment to pursue a program to promote the recent developments in the wind-diesel industry with the hope of improving the credibility of the technology. This would be completed through the documentation of performance of existing systems and a higher degree of project verification, including the performance of wind turbines in remote environments and other systems losses. Through better reporting of recent successes, more organizations should look favorably on supporting more and larger regional implementation projects, such as those currently being considered in Alaska.

The wind-diesel industry has come a long way since the publication of the landmark book by Ray Hunter and George Elliot, *Wind-Diesel Systems* [1], based on the IEA wind-diesel technology development work in the early 1990's. However, the market has not yet unfolded as it has for grid-connected wind technology, and only time will tell when it will.

ACKNOWLEDGMENTS

The original presentations from the 2002 DOE/AWEA/CanWEA wind-diesel workshop held in Anchorage, Alaska, can be viewed on the Wind Powering America Web site at http://www.eere.energy.gov/windpoweringamerica/wkshp_2002_wind_diesel_4.html.

The authors would like to thank all of those who participated in the 2002 Wind-Diesel Workshop. This paper is more about what the industry has been able to achieve than what the authors themselves have done.

This work and the 2002 DOE/AWEA/CanWEA Wind-Diesel workshop were supported by the U.S. Department of Energy through the Wind Powering America Initiative.

BIBLIOGRAPHY

- [1] Hunter, R.; Elliot, G. *Wind-Diesel Systems*. Cambridge, UK: Cambridge University Press, 1994.
- [2] Lundsager, P.; Bindner, H. "A Simple, Robust, and Reliable Wind-Diesel Concept for Remote Power Supply." World Renewable Energy Congress III, Reading, UK, 11-16 September 1994.
- [3] Beyer, H.G.; Degner, T.; Gabler, H. "Operational Behavior of Wind-Diesel Systems Incorporating Short-Term Storage: An Analysis via Simulation Calculations." *Solar Energy*, Vol. 54, No 6, pp. 429-439, 1995.
- [4] Shirazi, M.; Drouilhet, S. (1997). "An Analysis of the Performance Benefits of Short-Term Energy Storage in Wind-Diesel Hybrid Power Systems." 1997 ASME Wind Energy Symposium, Reno, Nevada, January 6-9, 1997.
- [5] Meiners, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel Workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/alaska.pdf.
- [6] Zimmermann, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel Workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/australia.pdf.

- [7] Baring-Gould, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/chile.pdf.
- [8] Information presented in several presentations, emerging markets, 2002 DOE/AWEA/CanWEA Wind-Diesel workshop:
http://www.eere.energy.gov/windpoweringamerica/wkshp_2002_wind_diesel_2.html.
- [9] Bindner, H. et. al. "Application of a proven 11-kW wind turbine in a modular small power system concept." RES for Water, Tourism and Water Desalination, Crete, Greece, 26-28 May 2003.
- [10] Nelson, V.; Foster, R.; Clark, N.; Raubenheimer, D. Wind Hybrid Systems Technology Characterization, technical report, Southwest Technology Development Institute, New Mexico State University, May 2002. http://solar.nmsu.edu/publications/wind_hybrid_nrel.pdf.
- [11] Pereira, A. de Lemos. "Modular Supervisory Controller for Hybrid Power Systems," Ph. D. Thesis, Riso-R-1202(EN), Riso National Laboratory, June 2000.
- [12] Bialasiewicz, J. T.; Muljadi, E.; Nix, R. G.; Drouilhet, S. (2001). Renewable Energy Power System Modular Simulator: RPM-SIM User's Guide (Supersedes October 1999). 172 pp.; NREL Report No. TP-500-29721.
- [13] RSVP's Analytical Models www.nrel.gov/villagepower/analytical/model.html. Accessed September 10, 2000.
- [14] Baring-Gould E.I., "Hybrid2: The Hybrid System Simulation Model." NREL/TP-440-21272, Golden, CO: National Renewable Energy Laboratory, (1996).
- [15] Power System Blockset, Users Guide 2.0, MathWorks, <http://www.mathworks.com/>.
- [16] Hansen, J.C.; Tande, J.O.G. "High Wind Energy Penetration Systems Planning." pp. 1116-1120, 1994. EUWEC'94, Thessaloniki, Greece.
- [17] Drouilhet, S.; Shirazi, M. (2002). Wales, Alaska High-Penetration Wind-Diesel Hybrid Power System: Theory of Operation. 77 pp.; NREL Report No. TP-500-31755.
- [18] Drouilhet, S. (2001). Preparing an Existing Diesel Power Plant for a Wind Hybrid Retrofit: Lessons Learned in the Wales, Alaska, Wind-Diesel Hybrid Power Project. 13 pp.; NREL Report No. CP-500-30586.
- [19] Web site of Northern Power Systems, Wind/Diesel Hybrid System Supplies Power to Alaskan Airport/Industrial Complex, <http://www.northernpower.com/template.php?t=7&g=22&c=122>.
- [20] Web site for Wind Powering America, Wind-Diesel 2002 Workshop Proceedings, http://www.eere.energy.gov/windpoweringamerica/wkshp_2002_wind_diesel_4.html.
- [21] Baring-Gould, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/coyhaique_chile.pdf.
- [22] Lundsager, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel Workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/cape_verde.pdf.
- [23] Zimmermann, Information presented in a presentation at the 2002 DOE/AWEA/CanWEA Wind-Diesel Workshop:
http://www.eere.energy.gov/windpoweringamerica/pdfs/workshops/2002_wind_diesel/denham_esperance.pdf.